Proton Therapy
Bragg Peak monitoring through Prompt-Gamma: Detection and Instrumentation

by José Patuleia Venâncio

Supervisors:

Patrícia Gonçalves

Pedro Assis

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TÉCNICO LISBOA

FCT Fundação para a Ciência e a Tecnologia

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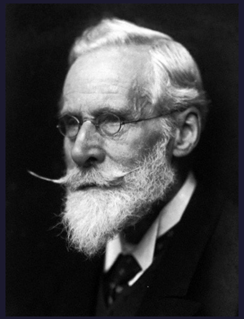
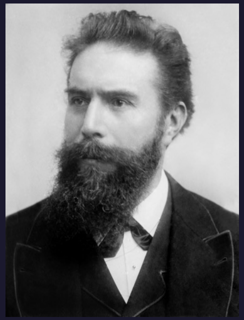
X-Rays: Origin



Sir William Crooke

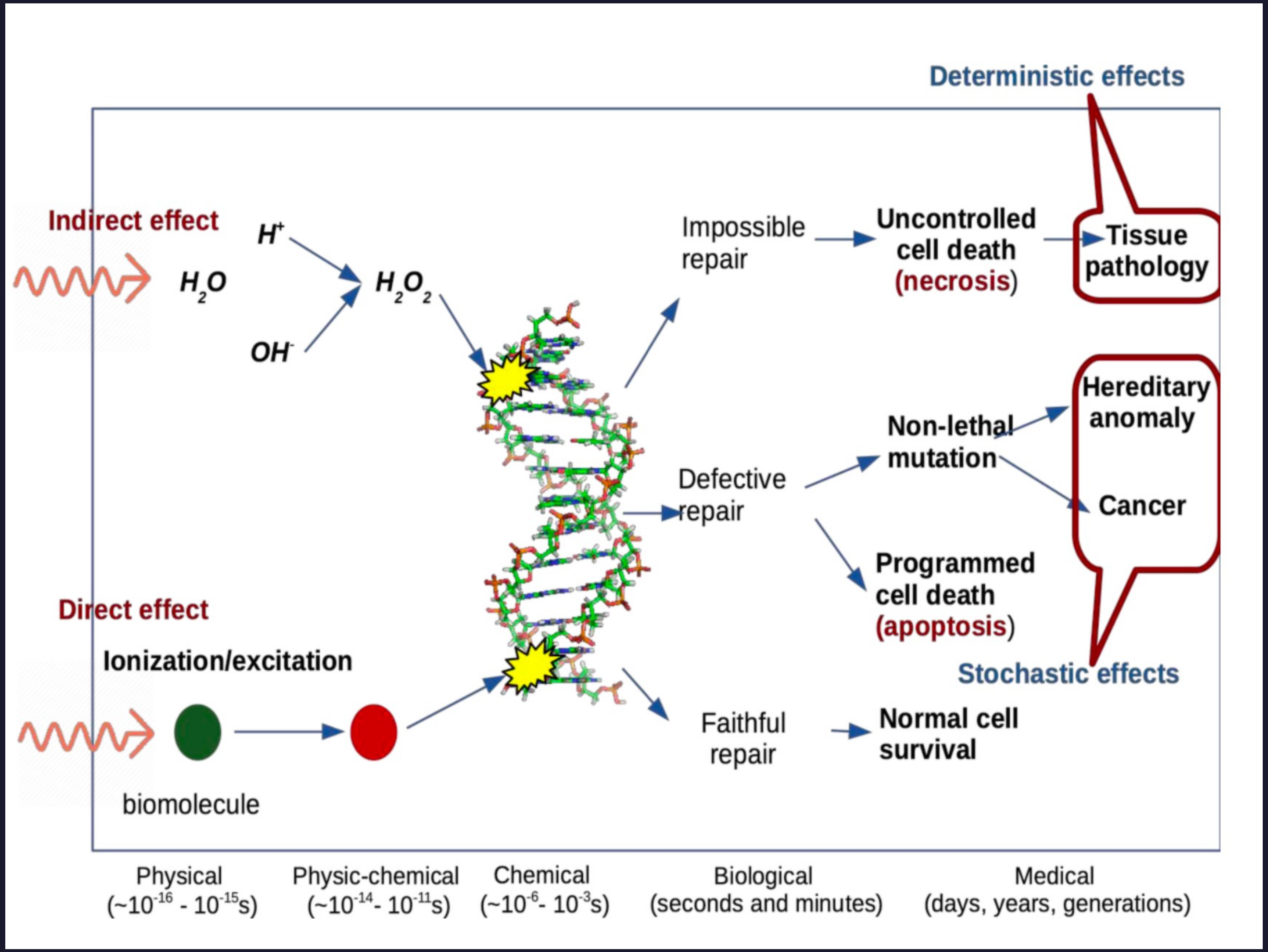


Röntgen

Wilhelm Conrad Röntgen won the Nobel Prize in Physics in 1901 for the discovery of the X-Ray.

- This discovery started much early in 1859 with Lenard Plucker while studying the passage of high voltage current through a vacuum tube which produced a green fluorescence in the inner wall of the tube;
- Then came Sir William Crooke which while studying this phenomenon named it cathode rays by 1875;
- Sir William Crooke recommended in 1879 the placement of the anode of the tube in such a way that it would bring the cathode stream into the focal point but due to hardware limitations that was only accomplished in 1893;
- In December 1893, Plucker design a new version of Crooke's vacuum tube, and by August 1895 he had catalogued the substances able to produce fluorescence when positioned in the path of the cathode rays;
- In September 1895, Plucker described that after passing through a thick body, for instance his own hand, the rays still excited chemicals to produce fluorescence. He also stated that the existence of radiation increased the electrical conductivity of the air or gases it went through. He still described, in October 1895, that photographic materials and light sensitive chemicals were altered by exposure to the cathode rays;
- In November 1895, Röntgen, while studying cathode rays, detected the presence of another particle that produced fluorescence in some substances and its effect in photographic materials;
- When comparing the notes from Plucker and Röntgen related to their experiments it was concluded that both where in the presence of X-Rays.

Biological damage due to Radiation



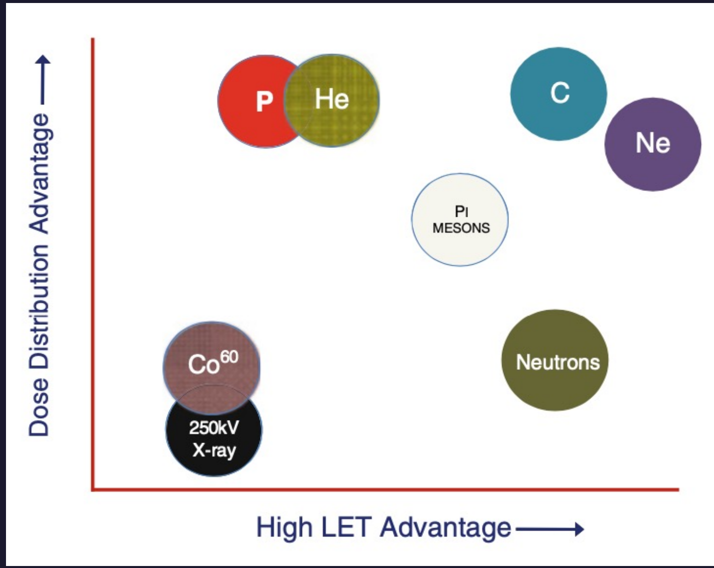
Types of radiotherapy

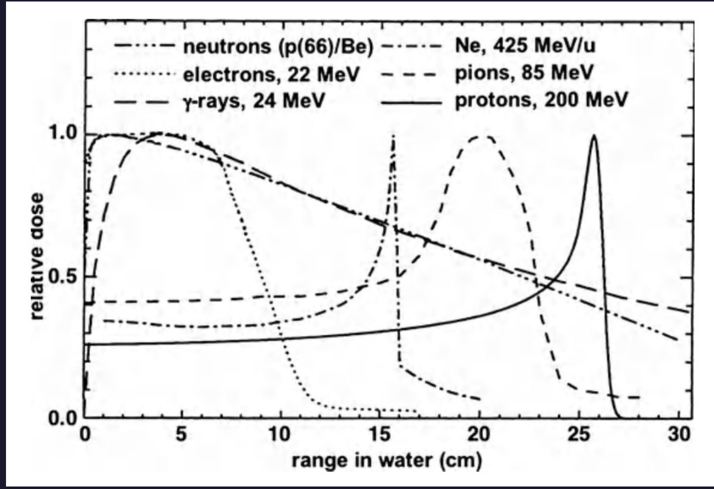
- Conventional Radiotherapy
  1. Beam particle are photons (X-rays or ɣ-rays) or electrons;
  2. Multiple beam exposure;
  3. Broad dose deposition profile;
  4. High dose deposition in healthy regions, increasing the dose ratio in healthy tissues relative to cancer cells.

- Particle Radiotherapy
  1. Beam particle are protons or ions;
  2. Dose profile peaks at the Bragg Peak;
  3. Low dose deposition before the Bragg Peak;
  4. Minimal dose deposition after the Bragg Peak.

Particle Radiotherapy
or Ion Beam Therapy

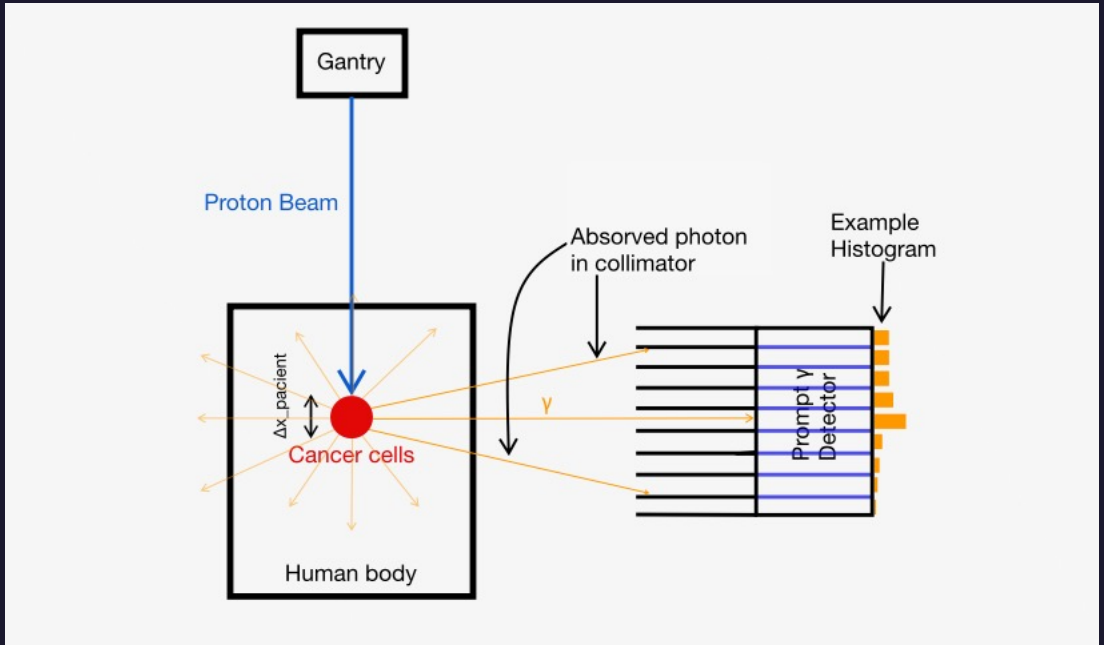
- Since the beginning of Clinical Radiotherapy, it has been the goal of radiation oncologists to restrict the deposited dose to the target volume;
- From all alternatives of Radiotherapy, ion beams are the closest to accomplish the objective;
- Protons and other accelerated ions can irradiate a tumour at any depth of the body with minimum dose given to the surrounding healthy tissues;
- Adjustments to penetration depth of ions to precisely "coincide" with the location of the tumour;
- Irradiation done by slices of different energy allow a successful exposure of the distal and proximal parts of a tumour of arbitrary shape.





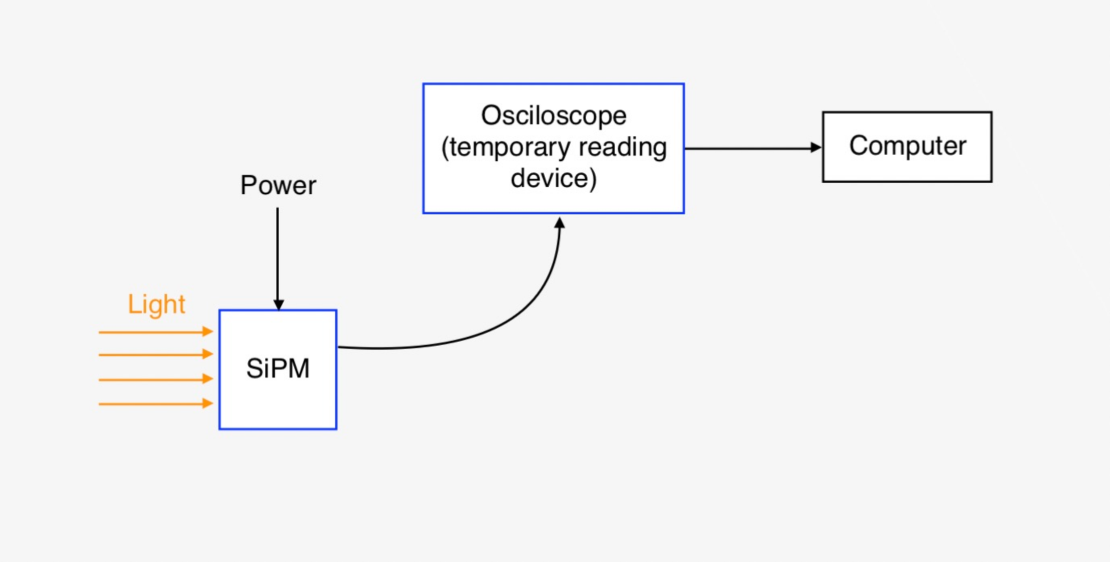
Instrumentation

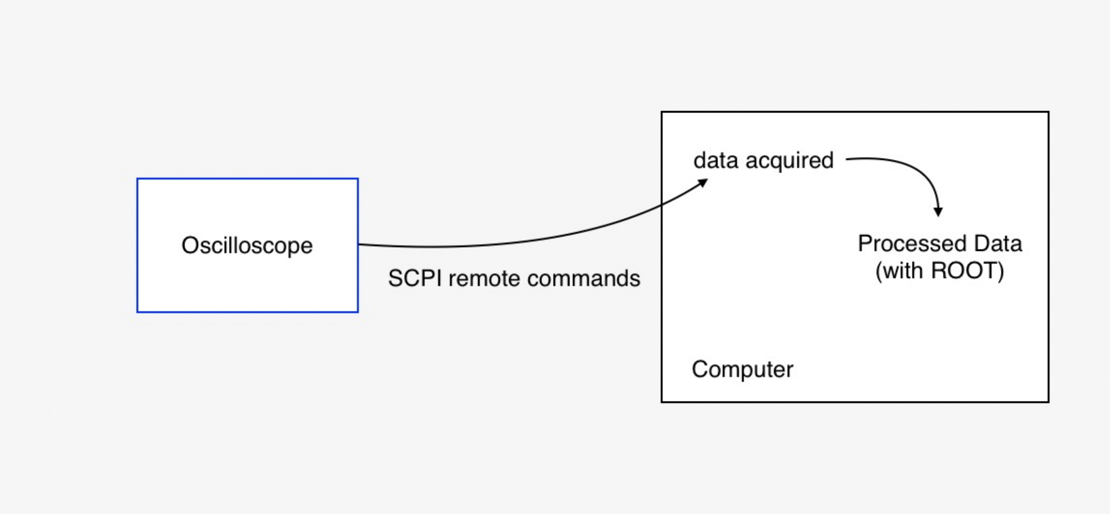
- Best placement for detector is orthogonal to the initial proton beam;
- The prototype solution has to be able to cope with a large number of sensors;
- A large volume of scintillators and a number of pixels O(100) is expected to feature in the solution;
- Techniques to enhance dynamic range and reduce noise are being pursued.

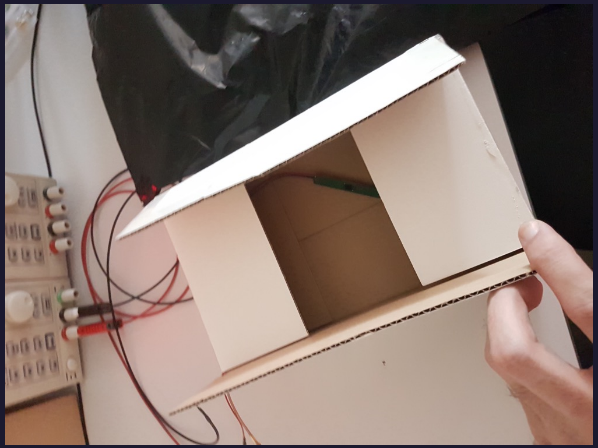


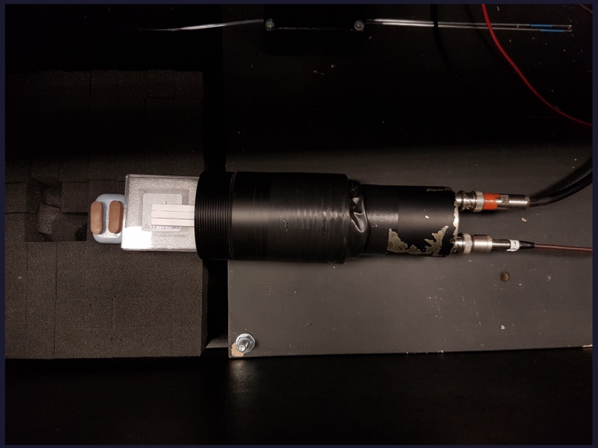
Work Development

- First setup based in an oscilloscope;
- Experimental setup using a SiPM with 6x6 mm area;
- Baseline setup with a PMT in a dark box;
- Experimental setups exposed to radioactive sources Cs-137 and Co-60;
- Simulations for validation and verification of the experimental data.



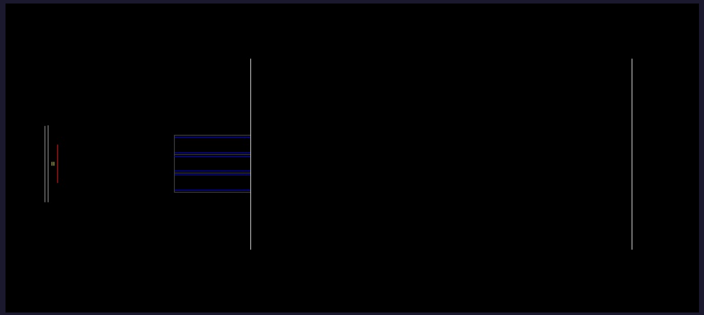


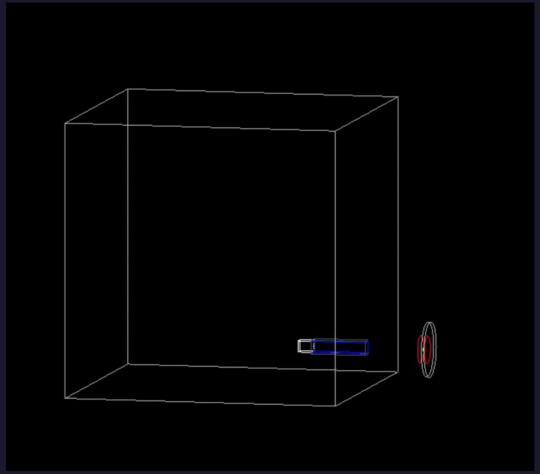




Geant4

- Simulation toolkit for particles interaction with matter in its path;
- Some areas of application include:
    1. Medical and Space science;
    2. High Energy;
    3. Nuclear and accelerator physics.
- Good documentation and user guides.



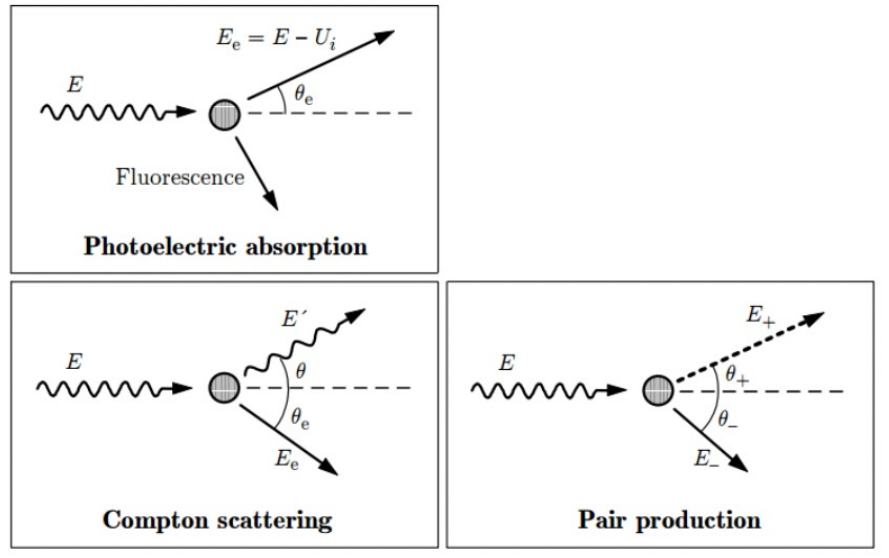


Conclusions and Future Endeavours

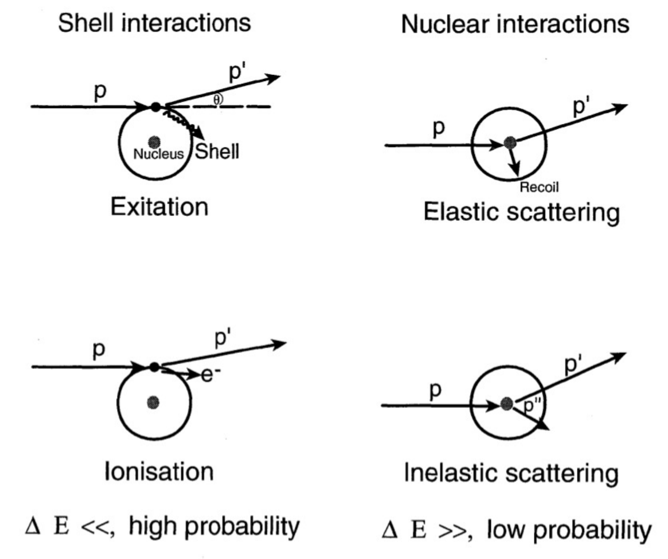
- Verify experimentally Cs-137 and Co-60 spectrums using SiPM+GSO and PMT+GSO setup;
- Validate the experimental data with the simulations in Geant4;
- Testing new setup with new circuit board and smaller SiPM;
- Verify response time of the SiPM used;
- Verify response of a system setup and best suitable type of acquisition setup in Geant4 simulations;
- Comparing the behaviour and performance of the system to a simpler system scalable to a large number of channels when exposed to radioactive sources;
- Simpler system probably based in the ROC ASIC chips from the OMEGA group with which LIP has experience.

Interaction with matter
(most relevant for Radiotherapy)

- Photons (Conventional Radiotherapy)
  1. Photoelectric effect;
  2. Compton scattering;
  3. Pair production.

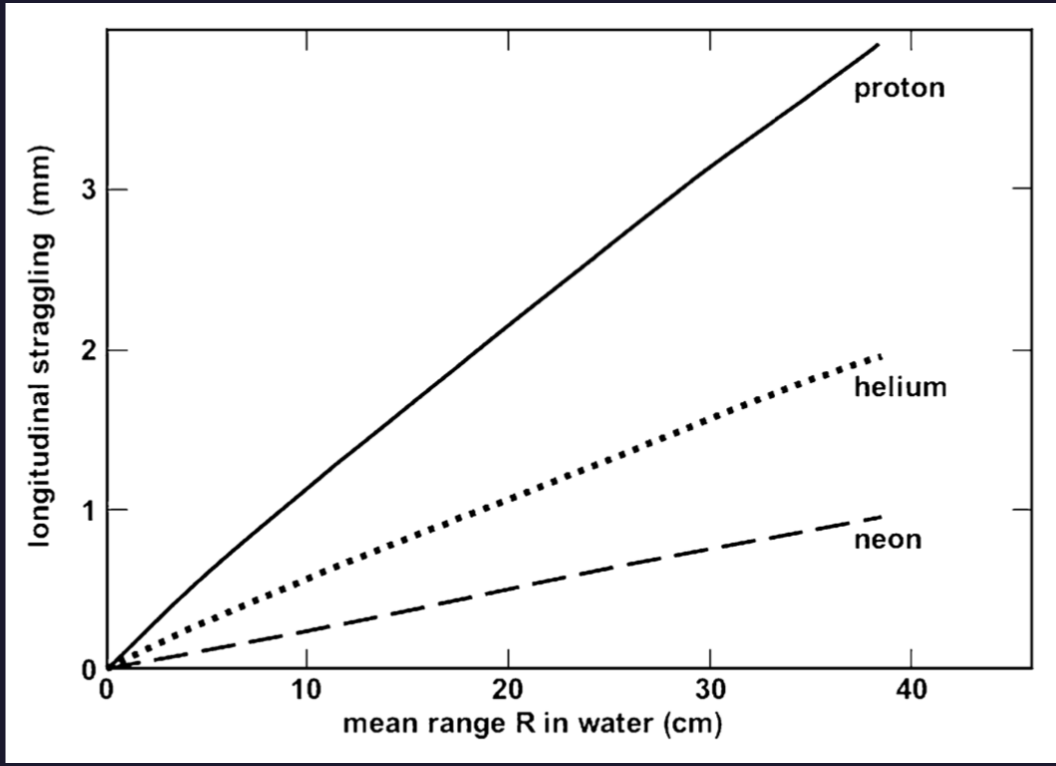


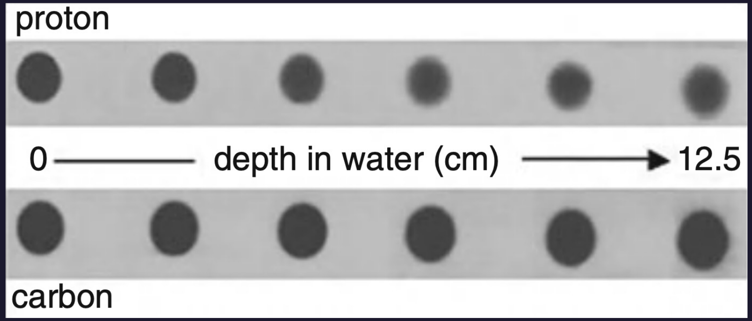
- Protons and low Z ions (Particle Radiotherapy)
  1. External electrons of atoms or molecules:
     I. Excitation;
     II. Ionization.
  2. Nuclear interactions:
     I. Elastic scattering;
     II. Inelastic scattering.



Proton, He and Carbon nuclei in Particle Radiotherapy

- Protons and heavier ions have a better depth-dose distribution when compared to photons;
- Ion beam therapy particles suffer straggling:
    1. Particles travel same distance in a monoenergetic beam;
    2. Not all experience same collisions;
    3. As such their range will be affected;
- He 50% smaller straggle than protons;
- Lateral spreading due to electron collision occurrence;
- Ions heavier than Helium will have higher stopping power which creates higher biological damages.



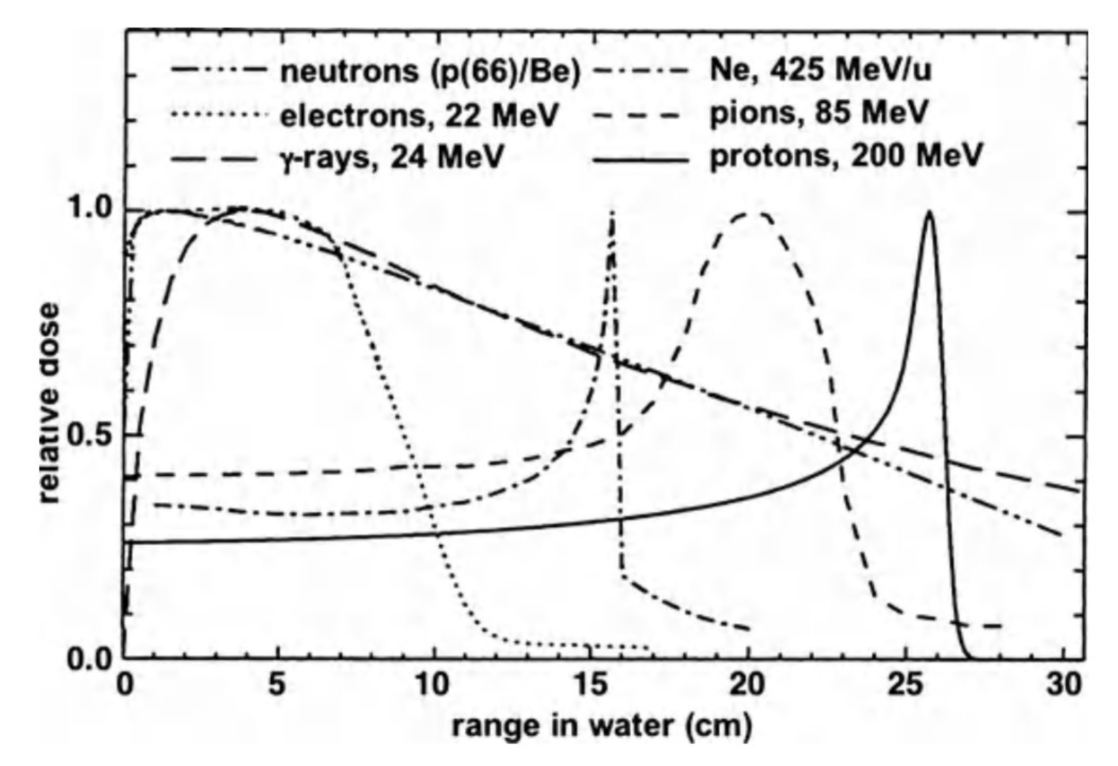


Proton vs carbon and He nuclei

- Advantages of Carbon and He are offset by Fragmentation due to nuclear interactions;
- Nuclear interactions cause a tailing after the Bragg Peak;
- Study made by Kempe confirmed dose distribution dependency on the number of nucleons $N(1/\sqrt{N})$;
- As such, clinical revival of ions with $Z > 6$ is unlikely;
- He, Li and Be are interesting alternatives to carbon ions;
- Proton is the most affordable of possible ions for Ion Beam Therapy.

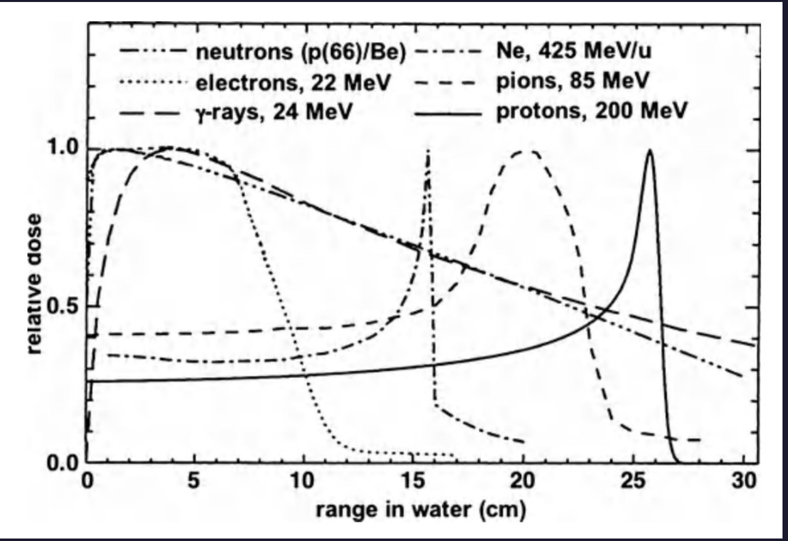
Beam Range Measurement

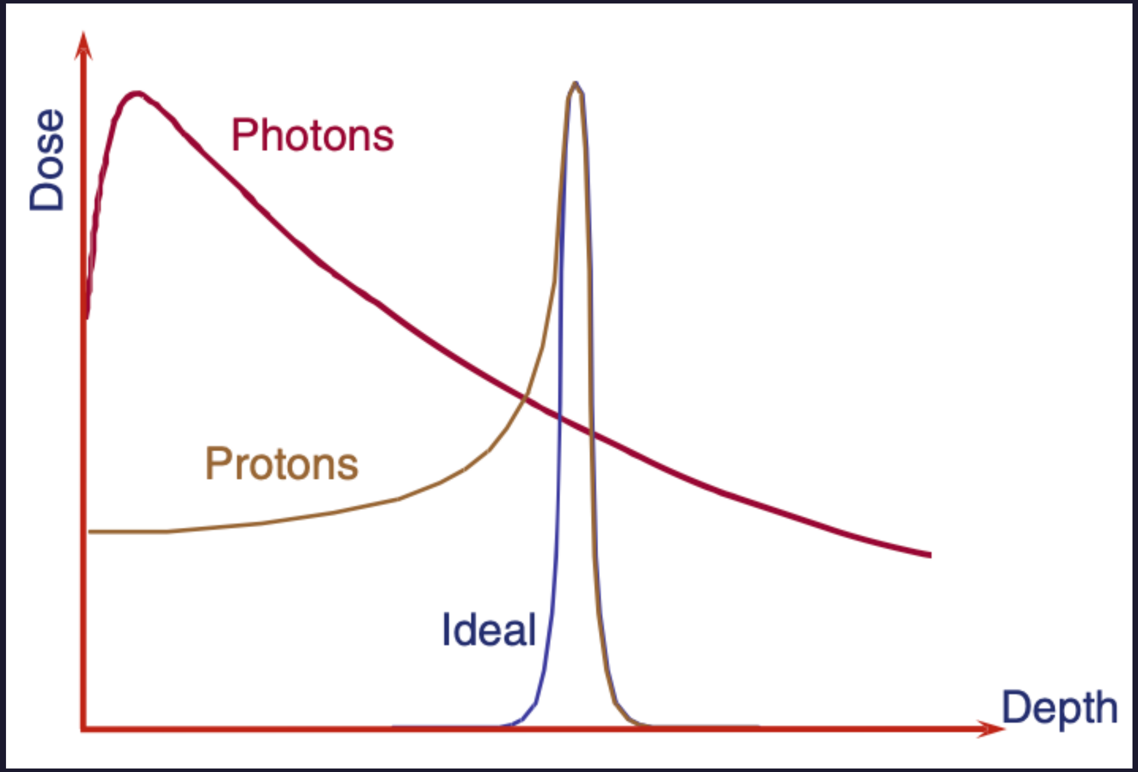
- Different factors influence the range of the beam;
- This project involves the measurement of the Bragg Peak position in vivo conditions;
- Prompt-gamma monitoring;
- Simulations show the possibility to achieve resolutions in the order of the millimetre.



Bragg Peak

- A monoenergetic beam of protons will have a peak in the dose deposited spectrum;
- Ion particles used for the Bragg Peak
- Spread-Out Bragg Peak is used to irradiate the tumour volume;



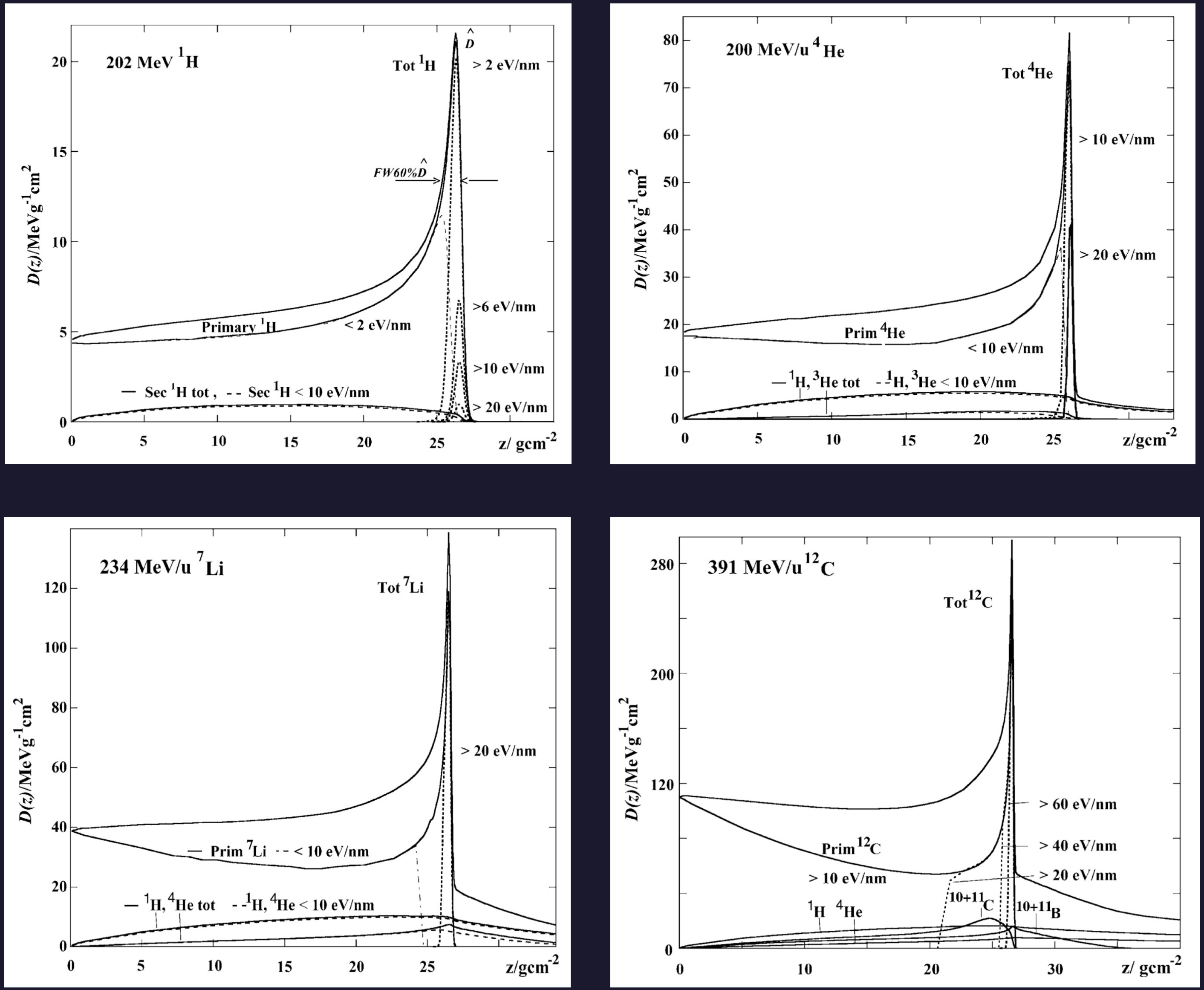


Kempe - dose distributional effects of ions of the first 10 elements of the periodic table

Ion	A	B	C	Total relative cost
Proton	1	1	1	1
Helium	1	1.5	1.4	1.3
Carbon	1	1.9	4.1	2.3
Oxygen	1	2.1	5.8	3.0
Neon	1	2.2	7.6	3.6

Assumptions: normal-conducting synchrotron, fourfold symmetric lattice, vault: 4 m high, 2 m clearance around the edges; 1 transport line: 10 m; 1 treatment room with conventional 45°–45°–90° gantry, 3 m distance to isocenter, ion range: 30 cm; shielding: 1.5 m concrete for protons. Cost components: (A) Fixed costs, (B) Technical components $\sim f$ (magnetic rigidity), (C) Shielding $\sim f$ (beam energy)

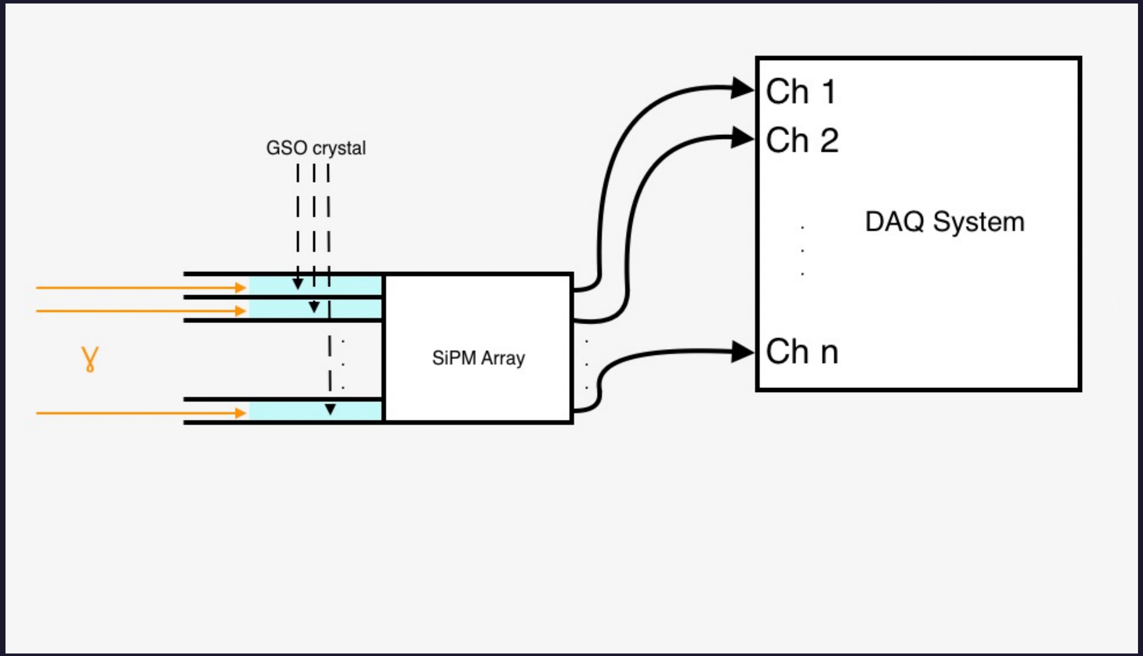
Kempe – depth absorbed dose distributional for Protons, Helium, Lithium and Carbon



Instrumentation - Detection

Collimators and pixelization allow spatial resolution in the beam direction:

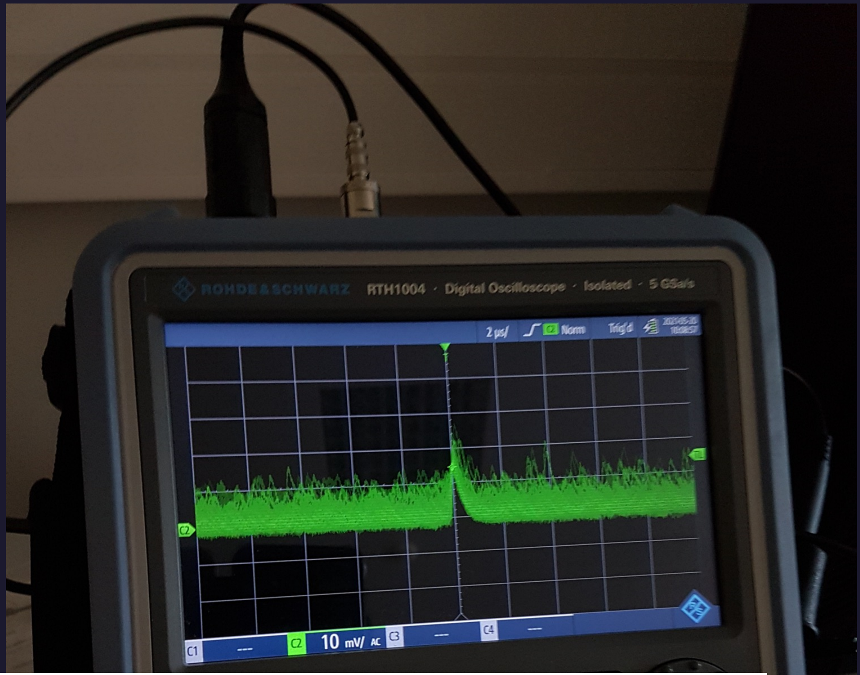
1. Each pixel is composed by a light sensor coupled with a scintillator crystal;
   - I. The candidate for light output is SiPM;
   - II. The Baseline scintillator will be either BGO or GSO.
2. A collimator is a series of high density material blades isolating each scintillator crystal and only near perpendicular gammas are detected.

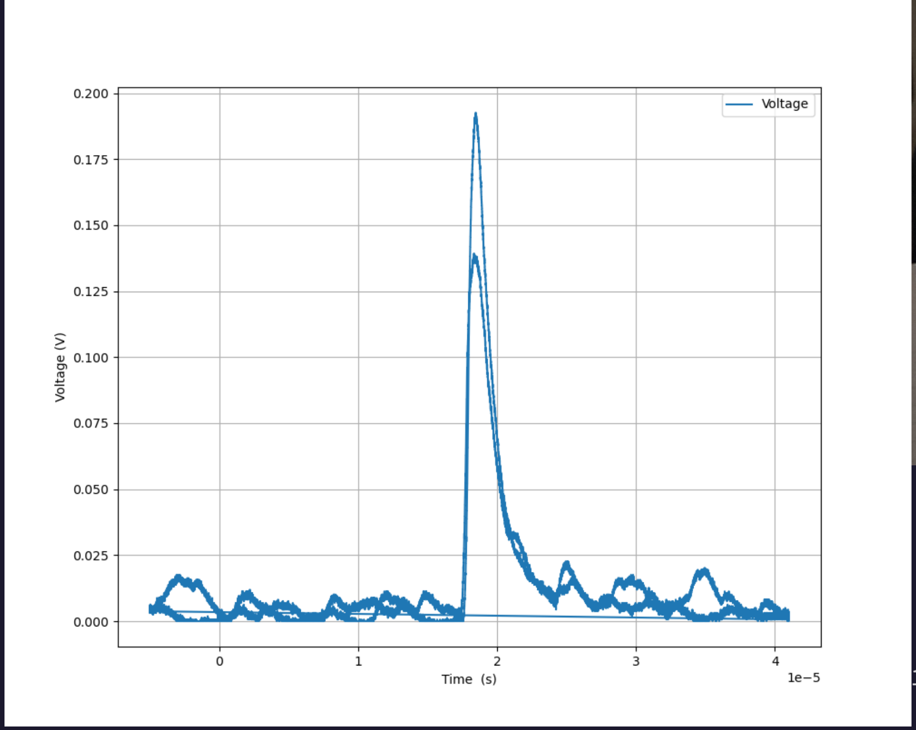


Experimental Setup
System Requirements

First Experimental Test System Requirements

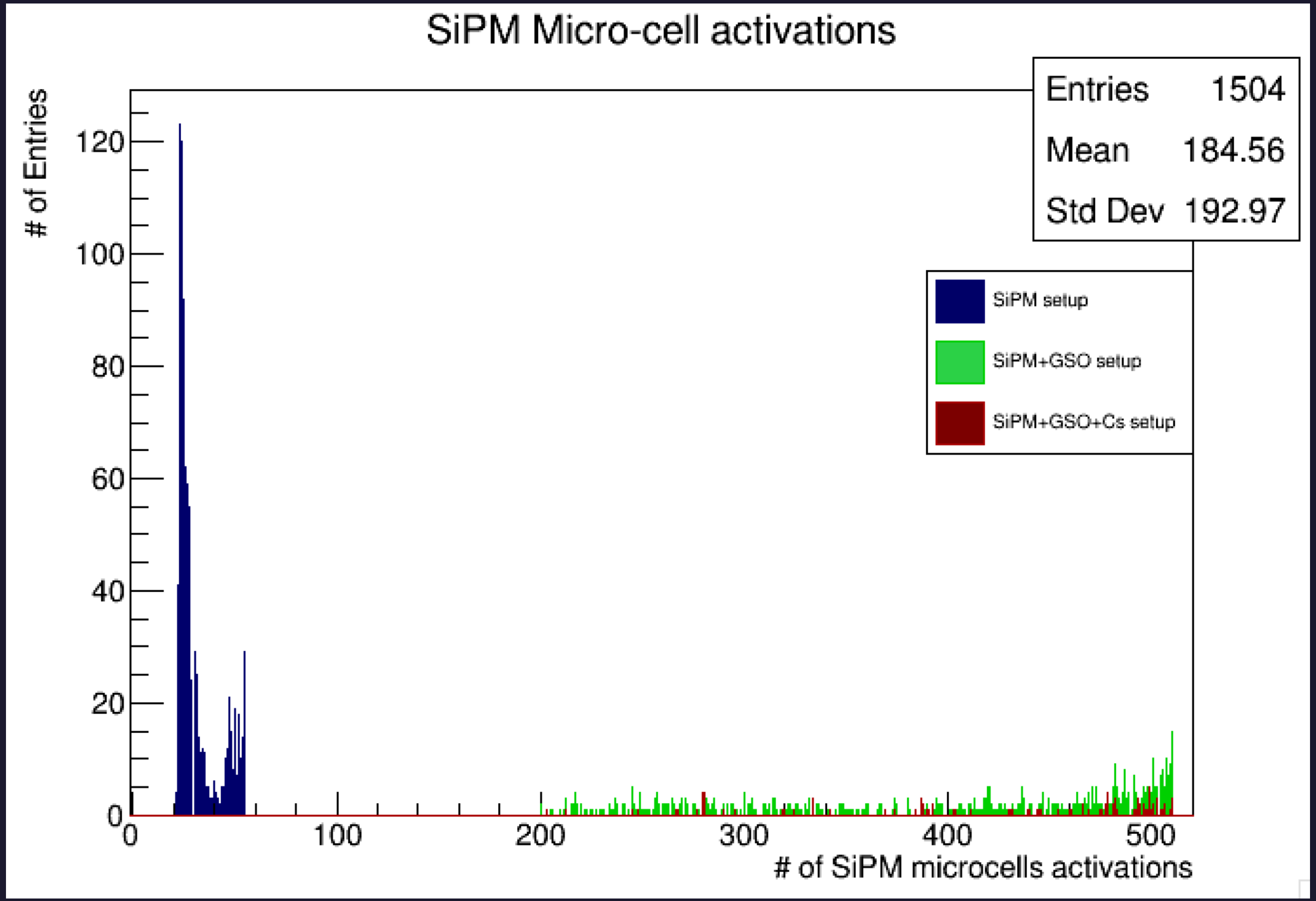
- First tests based with oscilloscope studied system requirements and possible simplifications;
- Data acquired in a dark box to isolate the contribution of an individual micro-cell from SiPM array;
- New setup is being built with SiPM arrays with size 3 and 1 mm.



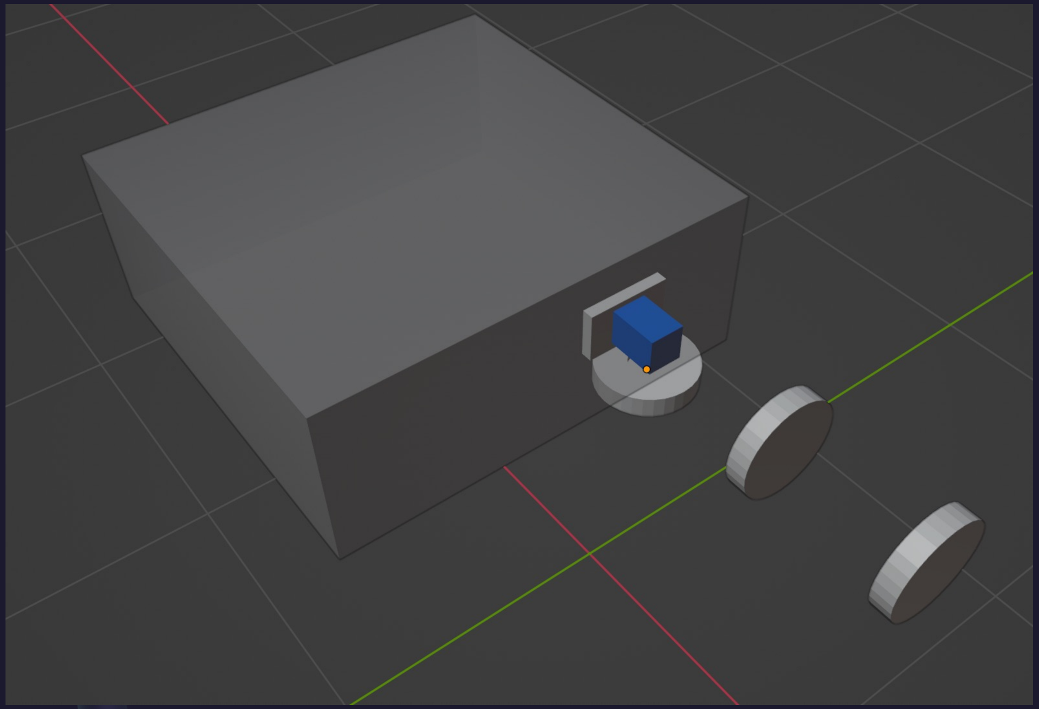


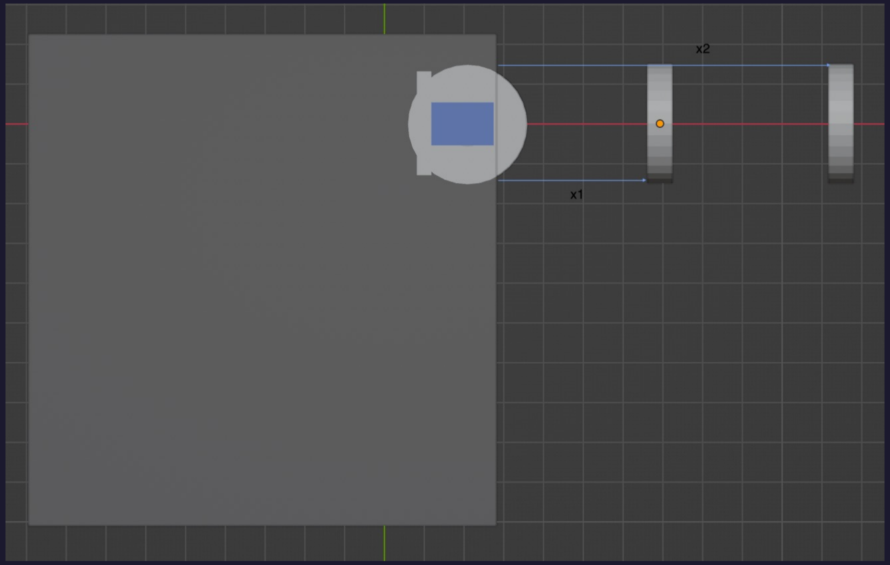
First Experimental test
Exposure to Cs-137

- Setup with GSO crystal coupled to SiPM in the dark box;
- Irradiation of detector with Cs-137 source.

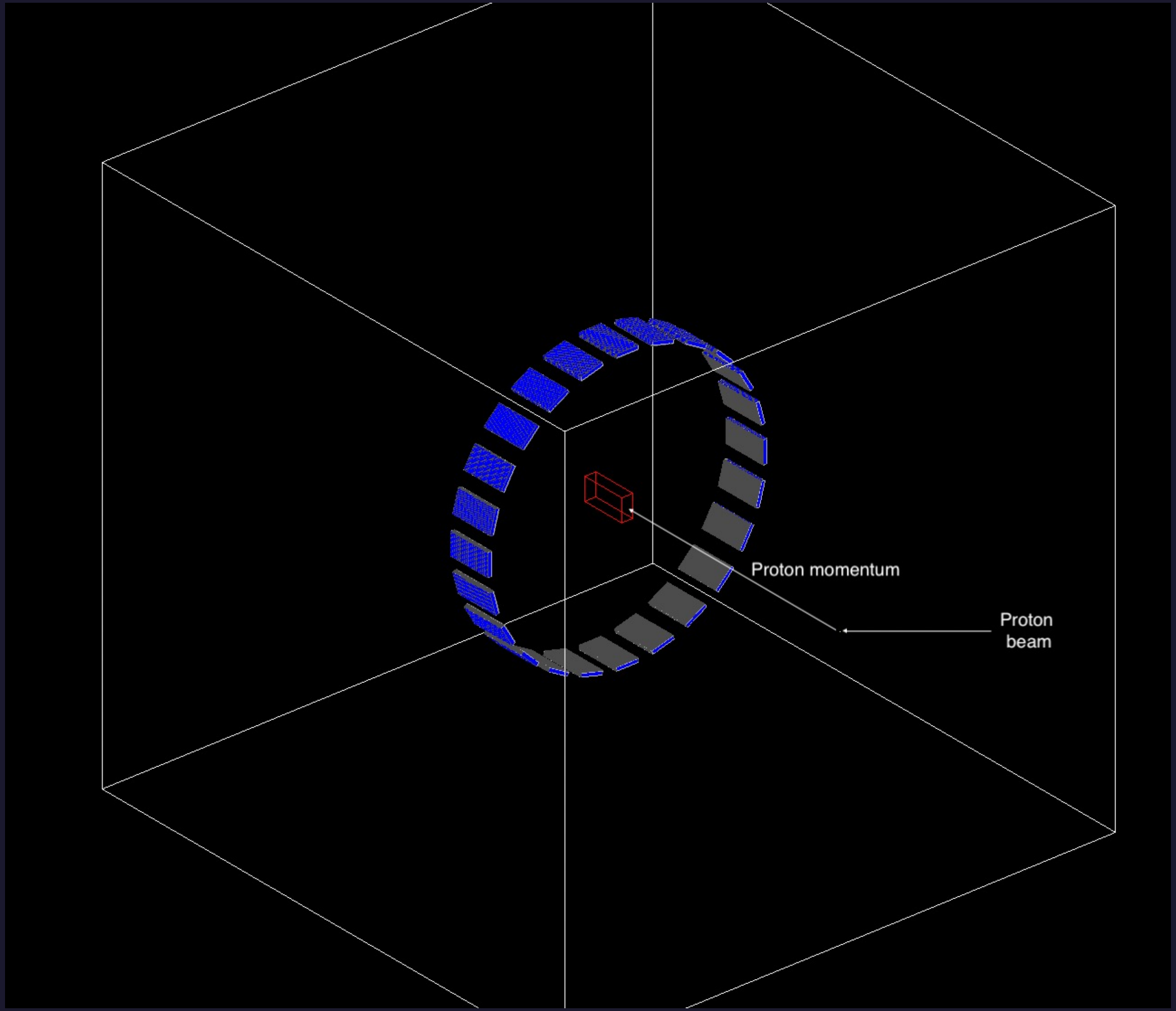


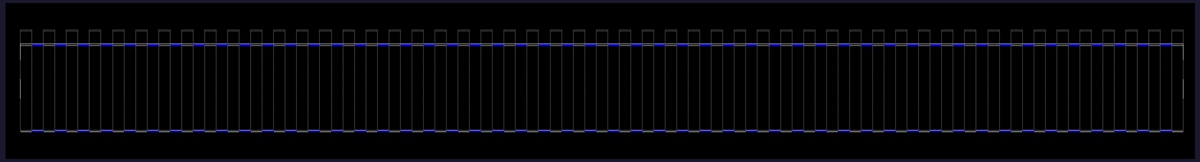
Experimental Setup
Exposure to Cs-137

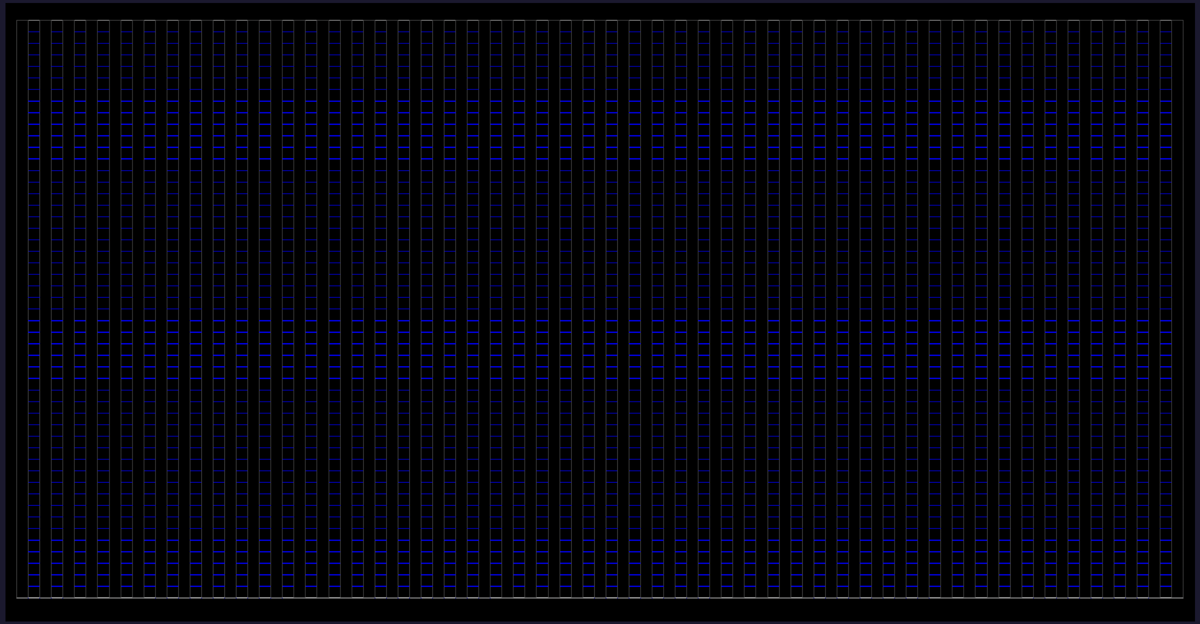




Geant4 Simulation







Proton interactions with matter

- Linear Stopping Power $\frac{dE}{\rho dx} = \frac{2\pi N_A z_p^2 e^4 Z}{m_e c_0^2 \beta^2 A_r} * [\boldsymbol{ln\left(\frac{2m_e c_0^2 \beta^2 W}{I_{adj}^2 (1-\beta^2)}\right) - 2\beta^2 - \frac{2}{Z}\sum_i C_i - \Delta + \pi\alpha Z_p \beta + \frac{2z_p Z\alpha^3 F(\beta,Z)}{\beta^3}}]$;
- Relative proton fluence $\phi(x) \approx 1 + 0.0018\,(R_0 - x)^{0.87}$;
- Molière distribution $f(\theta, d) = \frac{1}{4\pi\theta_M^2} * [f^{(0)}(\theta') + \frac{f^{(1)}(\theta')}{B} + \frac{f^{(2)}(\theta')}{B^2} \pm \cdots]$;
- Characteristic multiple scattering angle (θ_M) $\theta_M^2 = \frac{1.56*d*B*Z^2}{2*A*(pv)^2}$;
- Pathlength $P_x = \int_{E_f}^{E_0} (\frac{dE}{\rho dx})^{-1}\, dE$;
- Mean range $R_0 = \int_{E_f}^{E_0} \overline{\cos\theta}\, (\frac{dE}{\rho dx})^{-1}\, dE$;
- R_0 for protons in water is $R_0 = \alpha E_0^p$, where $\alpha \approx 0.0022$ and $p \approx 1.77$ and $\alpha \approx \frac{\sqrt{A}}{\rho}$

SCPI commands for data acquisition from Oscilloscope R&S-RTH1004

- **Use of python pyvisa library;**
- **connection = pyvisa.ResourceManager();**
- **rth1004=connection.open_resource(ip_address, write_termination='\n', read_termination= '\n', chunk_size= 128, timeout=25000);**
- **screen_data=rth1004.query("CHAN2:DATA:HEAD?") # example of data acquire [-0.0025,0.0025,500000,1]-> [start time, stop time, number of samples, values per sample interval].**

References

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